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Numerical study of bolt loosening in shear-loaded joints under cyclic loading.

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Abstract. Although many steel civil structures are not exposed to large cyclic loads or to a high number of cycles which can develop significant fatigue damage, this phenomenon cannot be completely ruled out, especially in connection systems. Bolted joints, widely used for their practicality in assembly and disassembly, may show loss of fastening over time when subjected to cyclic stresses. Depending on the way in which the load is transmitted, these connections may be subjected to axial tensile, shear, torsion or lever action stresses. The progressive decrease in clamping force, caused by relative slippage or relaxation of the assembly, increases maintenance requirements and may compromise structural safety if not properly controlled. In this work, in order to study the mechanical behavior and the evolution of the preload loss in bolts under cyclic actions, a finite element model is developed to simulate the loosening in bolted joints subjected to transverse or shear loads. The model allows to analyze the influence of different parameters on the relative sliding between the bolted parts, as well as to evaluate the impact of these conditions on the service life of the connection. Obtained results are compared with existing criteria in literature to validate the numerical approach.

Keywords: Bolted joints, Preload loss, Cyclic loading.

1 Introduction

Although many steel structures used in civil engineering are not subjected to large cyclic loads or to a number of cycles sufficient to induce significant fatigue damage, this phenomenon cannot be entirely dismissed—particularly in connection systems. In particular, bolted joints, widely adopted in industrial structures for their ease of assembly and disassembly, may exhibit a loss of clamping force over time under cyclic actions. In this context, preload in bolted assemblies is decisive to ensure connection reliability and global stability; however, due to environmental and operational changes, preload often relaxes, which can lead to failures and structural damage with safety implications. Therefore, tools are required to predict and accurately assess preload relaxation in bolted joints under transverse loading [1].

Regarding established literature, Nassar and Matin [2] proposed a mathematical model to predict the variation of preload during the self-loosening process, investigating the relationship among bearing-friction torque, thread-friction torque, and lead-torque components; nonetheless, the simplifications introduced led to discrepancies with the actual joint response. Complementarily, Jin et al. [3] proposed a method to define the preload in bolted joints by combining a local cooling technique with an equivalent-friction approach, in order to simulate the stress distribution in pretensioned bolted assemblies. In Chen et al. [4], it is emphasized that modeling and meshing the helical geometry of the bolt and thread in finite elements—while accounting for the lead angle—are challenging. Two main approaches are described: modeling the bolt shank and the thread separately and connecting them via a tie/constraint, as in Zhang et al. [5], which permits hexahedral meshes but transfers force and displacement across the interface by interpolation (reducing accuracy and potentially generating critical stress discontinuities and spuriously high stresses at some nodes); or treating the shank and threads as a single part and meshing the full helical geometry, which typically requires tetrahedral elements, as in Yokoyama et al. [6]. Preload refers to the elastic

restoring force of the bolt in service and is commonly controlled by tightening torque or nut rotation angle. In Chen et al. [4], the tightening process was simulated by prescribing a ramped circumferential displacement θ_0 on the nut's lateral surface, holding it for a dwell time, and subsequently releasing it. In addition, Chen et al. [1] analyzed the velocity field along points on the outer ring of the bolt head and found that the self-loosening process under lateral loading resembles a "creep–slip" mechanism, i.e., an indirect process governed by the accumulation of localized slip.

When studying the loosening of threaded assemblies under transverse vibration, axisymmetric thread models are inadequate; the influence of the thread helix angle must be considered. To compute with accuracy the relative displacement and the contact area between mating threads under realistic operating conditions, it is necessary to first adopt an appropriate curvilinear coordinate system—namely, a modeling framework tailored to this problem [7]. Moreover, as noted by Wang et al. [8], connection interfaces are often treated via equivalent linearization, or their intrinsic nonlinearity is neglected altogether. Such practices, by ignoring the true nonlinear character of the interface, frequently yield large experimental discrepancies or fail to predict the structural dynamic behaviors of the calibrated model under certain testing conditions.

In this work, a simplified finite element model is developed to simulate loosening in a bolted joint subjected to shear, with the aim of preliminarily studying the mechanical behavior and the evolution of preload loss in bolts under cyclic actions, as a basis for more advanced models that can provide higher accuracy and broader generalization. The present model allows analyzing the influence of the initial preload on the time variation of clamping force in the case of a monotonic action, and subsequently comparing it with the loosening produced by an imposed displacement of cyclic character. In addition, the loss of preload is evaluated as a function of the magnitude of the applied transverse displacement.

2 Finite-Element Model Simulation

A simplified joint geometry is proposed, consisting of two identical flat plates connected by a bolt and a nut, in order to preliminarily simulate the loosening in a bolted joint subjected to shear and the evolution of preload loss in bolts under cyclic actions, as a basis for more advanced models in future studies. The plates have a width of 40 mm, a height of 15 mm in the joined section, and a length of 82 mm. The bolt has a nominal diameter of 12 mm, while the holes in the plates are 13 mm, introducing clearance. The nut is modeled as a separate part from the bolt. In both cases, since this is a baseline model for preliminary studies and in order to improve computational efficiency, the nut interior and the bolt shank are considered unthreaded. Figure 1 shows the adopted configuration. It should be noted that the omission of the thread geometry reduces the local accuracy of stress distribution and may affect the absolute values of preload loss. Nevertheless, this simplification enables a more efficient computation while still capturing the global trends of clamp-force relaxation under monotonic and cyclic transverse loading, which are the focus of the present study. Figure 1 shows the adopted configuration.

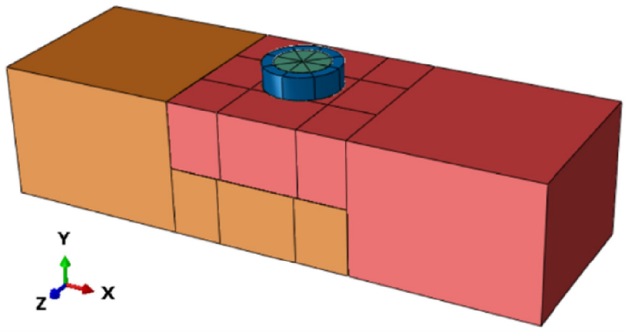


Figure 1. Simplified bolted-joint geometry and parts considered in the FE model, including two identical flat plates, a bolt, and a nut.

To model contact, the holes are not aligned in the assembly; instead, the bolt establishes a single contact point with each plate. Figure 2 shows the adopted scheme.

The plate material is F24 steel [9], with Young's modulus $E = 200\,GPa$, Poisson's ratio $\nu = 0.3$, density $\rho = 7.85\,kgf/m^3$, and yield stress $\sigma_y = 235\,MPa$. For the bolt (ISO 10.9), a yield stress of $830\,MPa$ is adopted; for the nut (ASTM A563, grade DH), the yield stress is $635\,MPa$. Bolt preload is simulated by defining an internal cross-section in the shank and prescribing the tensile direction and magnitude on that section, as shown in Figure 3.

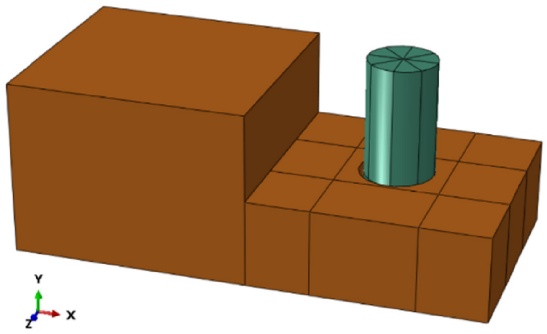


Figure 2. Detail of the contact scheme used to simulate shear transfer, with the bolt misaligned to establish point contact with each plate.

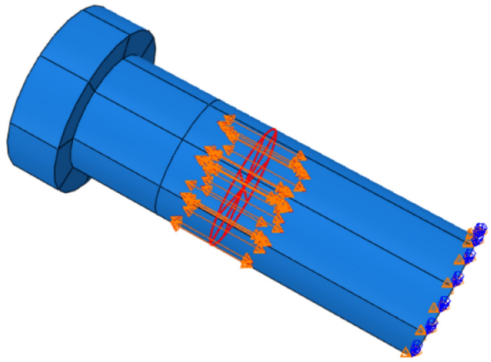


Figure 3. Definition of preload in the FE model: tensile force applied at an internal cross-section of the bolt shank, with direction and magnitude indicated.

Liu et al. [7] apply the transverse load at a reference point (RP) kinematically coupled to the free-end surface of the non-embedded plate, while the opposite surface of the other (lower) plate is fixed. In the present work, that transverse load is replaced by a prescribed displacement, also applied at an RP coupled to the free-end surface of one plate, whereas the opposite end of the other plate is clamped. In addition, the bolt head is restrained by suppressing translations in X and Y and rotation about Z, as shown in Figure 4.

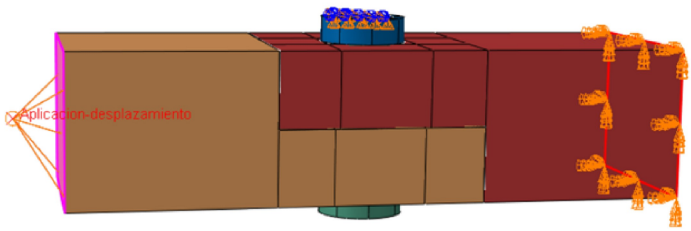


Figure 4. FE model boundary conditions and reference point where the cyclic displacement is prescribed.

Regarding contact properties, a *Penalty* formulation with friction coefficient $\mu = 0.35$ is adopted for the tangential behavior, and *Hard Contact* with the option *allow separation after contact* is used for the normal behavior.

Geometric nonlinearity was activated in all simulations to account for large-displacement effects, which are relevant due to contact sliding, bolt tilting within the clearance, and the progressive relaxation of preload under cyclic shear actions.

As solid discretization is required, hexahedral elements are employed, type C3D8R. Each plate contains $7{,}868$ elements, the nut 60 elements, and the bolt $1{,}416$ elements.

Regarding loading, two general models are defined. In Model A, the bolt is assigned an initial preload and a monotonic transverse displacement U is applied to the joint; three cases are considered with different displacement

magnitudes. The sequence of steps is as follows: in the *Initial* step, the boundary conditions are imposed—a clamp at the end of one plate and a restraint at the bolt head. Next, in the *Preload* step (duration $5\,s$), a tensile force of $61\,kN$ is applied on an internal cross-section of the bolt, a value taken from Table J.3.1 of CIRSOC [9] for the minimum tightening force by nominal diameter. Finally, in the *Displacement* step (duration $4\,s$), an X-direction displacement is imposed on the free-end face of the non-embedded plate.

By contrast, Model B also starts from an initial preload and then imposes a cyclic transverse displacement U on the joint. The *Initial* step reproduces the same boundary conditions as in Model A. In the *Preload* step, $61\,kN$ is prescribed first and subsequently increased to $79\,kN$ to compare the time evolution of the response. The cyclic displacement history is partitioned into multiple steps (see Table 1). Initially, a single $4\,s$ displacement step with a tabular amplitude was attempted; however, the model exhibited convergence issues, and the history was subdivided into several steps, improving the numerical stability of the analysis.

Table 1. Cyclic displacement program: steps and end-of-step displacement

Step ($0.5\,s$)	**End-of-step displacement** (mm)
1	-0.5
2	0
3	0.5
4	0
5	-0.5
6	0
7	0.5
8	0

3 Numerical Results

In all cases, the properties and conditions defined in the finite-element simulation section are retained: F24 steel plates; tangential contact with a *Penalty* formulation and friction coefficient $\mu = 0.35$; normal behavior as *Hard Contact* with separation allowed; solid meshing; and identical boundary conditions. Figure 5(a) shows Model A-1 with an initial preload of $61\,kN$ and an imposed transverse displacement $U = 0.2\,mm$. During the first $5\,s$, the axial force increases linearly until it reaches $61\,kN$, corresponding to the preload stage. From that instant, with the preload held and once the displacement is applied, the axial force begins to decrease, indicating bolt loosening.

Figure 5(b) shows Model A-2 with an initial preload of $61\,kN$ and an imposed transverse displacement $U = 0.5\,mm$. During the first $5\,s$ the preload is applied until the axial force reaches $61\,kN$. From that moment, with the preload held and the displacement initiated, the axial force decreases more rapidly than in Model A-1 due to the increased shear at the bolt–plate interface. An abrupt drop is observed immediately after $t = 5\,s$, followed by a sustained decline with a gentler slope.

Figure 5(c) shows Model A-3 with an initial preload of $61\,kN$ and an imposed transverse displacement $U = 0.8\,mm$. During the first $5\,s$, the preload is applied until the axial force reaches $61\,kN$. Thereafter, the preload is held and the displacement is initiated. The axial force decreases more strongly than in Models A-1 and A-2: an abrupt drop appears immediately at the onset of the displacement, followed by a sustained decline.

Figure 6(a) shows Model B-1 with an initial preload of $61\,kN$ and a cyclic transverse displacement with a maximum amplitude of $0.5\,mm$ applied once the preload is reached. During the first $5\,s$, the axial force increases linearly until it reaches $61\,kN$. Thereafter, the preload is held and the displacement steps begin. A nonlinear response is observed, with decreases and increases in the axial force that coincide with the moments of displacement reversal. By the end of the step, the residual axial force is $12.25\,kN$, which confirms that cyclic displacement accelerates clamp-load degradation compared with the monotonic case of the same amplitude. Finally, to assess the effect of a higher pretension, the initial preload is increased by thirty percent, from $61\,kN$ to $79\,kN$, while maintaining the same transverse displacement history as in case B-1. Figure 6(b) shows Model B-2 with an initial preload of $79\,kN$ and a cyclic transverse displacement with a maximum amplitude of $\pm 0.5\,mm$ applied once the preload is reached. After attaining the $79\,kN$ preload and initiating the cyclic displacement history, a nonlinear

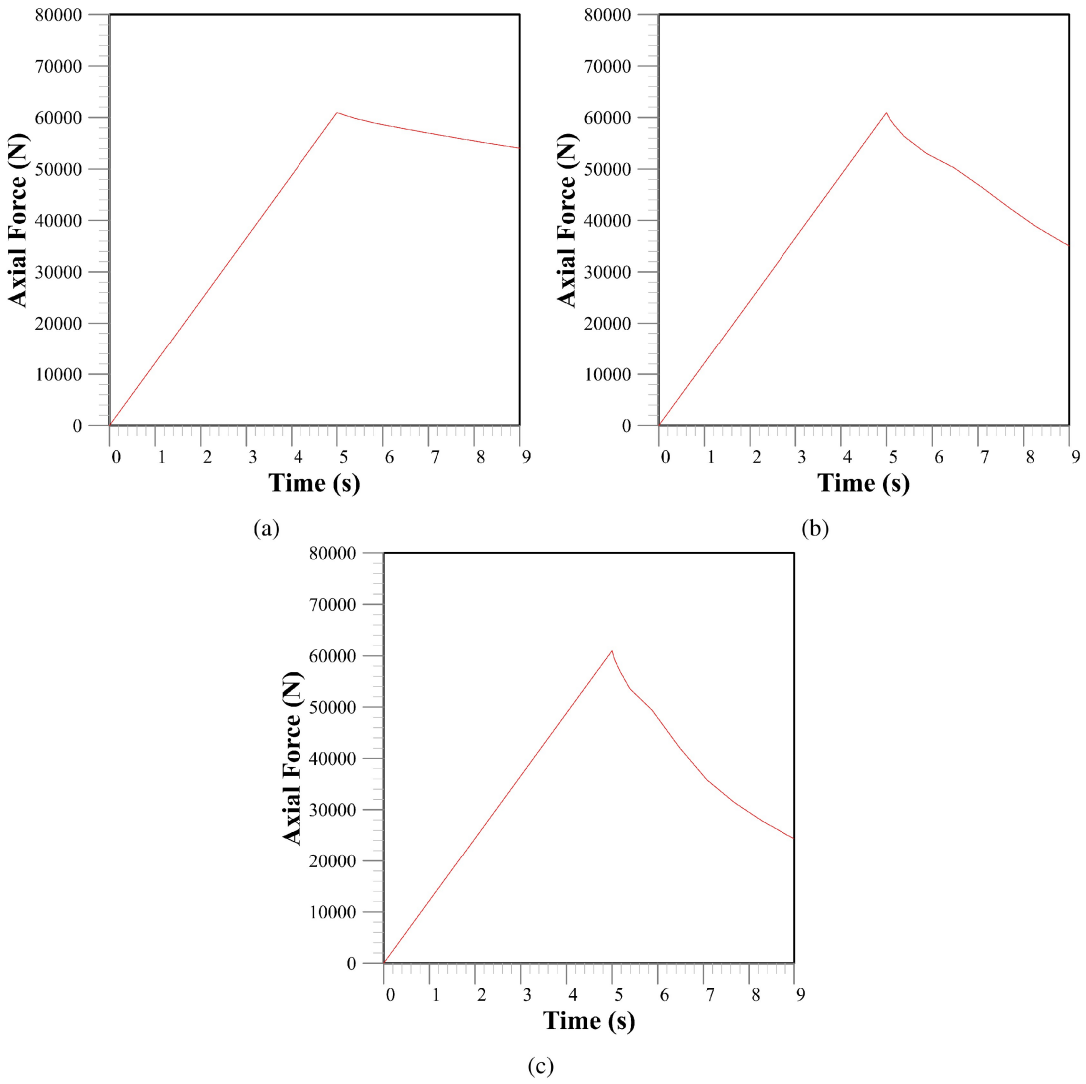


Figure 5. Evolution of axial bolt force for an initial preload of 61 kN under cyclic transverse displacement, showing the progressive reduction of clamping force with the number of cycles.(a) transverse displacement $U = 0.2\,mm$; (b) $U = 0.5\,mm$; (c) $U = 0.8\,mm$.

response similar to the previous model is observed. In this case, the residual axial force is approximately $25.3\,kN$, indicating smaller loosening when the initial preload is higher.

Table 2 summarizes the main results, reporting the residual axial force in the bolt and its percentage relative to the initial preload, together with the percentage loss. Models with monotonic displacement exhibit a loss that increases with the amplitude of U, whereas cyclic models show more severe clamp-loss for the same amplitude.

In Model A, a direct relationship is observed between the magnitude of the transverse displacement and the percentage loss of axial force. For $U = 0.2\,mm$, the loss is 12%, whereas for $U = 0.8\,mm$ it rises to 60%. The trend is nonlinear: a fourfold increase in displacement produces roughly a fivefold increase in percentage loss, indicating that relative slip at the contact surfaces triggers a relaxation process that intensifies with the shear transmitted through the bolt. Comparing the monotonic case with $U = 0.5\,mm$ (case A-2) against the cyclic case with amplitude $\pm 0.5\,mm$ (case B-1), the difference is marked: the loss is 43% in the monotonic response and 80% under cyclic loading, evidencing an accumulative effect driven by repeated micro-slips that degrade the contact and relax the preload. Increasing the initial preload by 30%—from $61\,kN$ to $79\,kN$—under the same cyclic protocol yields a relative improvement, reducing the loss from 80% to 68%; thus, a higher initial preload delays loosening and improves the residual capacity, although it does not eliminate the phenomenon. Under cyclic actions,

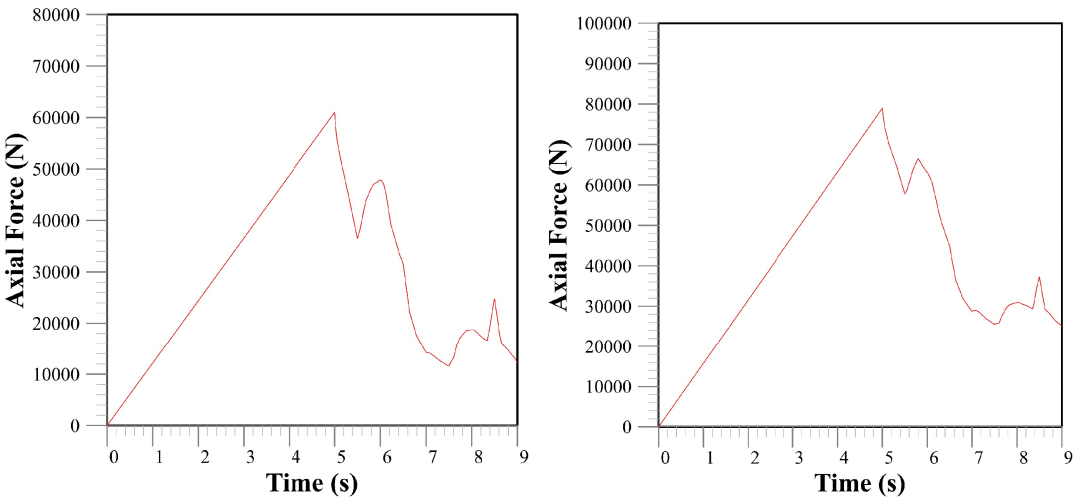


Figure 6. Evolution of axial bolt force for an initial preload of 61 kN under cyclic transverse displacement, showing the progressive reduction of clamping force with the number of cycles. (a) Preload of 61 kN (b) Preload of 79 kN

Table 2. Summary of results: residual clamp force and percentages relative to initial preload

Model	**Initial preload** (kN)	**Load type**	**Max. displacement** (mm)	**Residual axial force** (kN)	**residual** (%)	**loss** (%)
A-1	61	Monotonic	0.2	53.7	88	12
A-2	61	Monotonic	0.5	34.8	57	43
A-3	61	Monotonic	0.8	24.4	40	60
B-1	61	Cyclic	$\pm$0.5	12.25	20	80
B-2	79	Cyclic	$\pm$0.5	25.3	32	68

a nonlinear evolution is also observed, with axial-force fluctuations synchronized with displacement reversals; these partial recoveries do not constitute a permanent restoration of preload but rather a transient redistribution of stresses due to contact geometry and friction. Overall, the patterns align with prior reports that identify accumulated localized slip at the interface as the governing mechanism of loosening and show that transverse cyclic loads accelerate clamp-loss relative to equivalent monotonic solicitations [1, 7].

4 Conclusions

Based on the assumptions made in the joint model and the results obtained, it can be concluded that the numerical model adequately reproduces the expected behavior of bolted joints subjected to shear. It successfully captured nonlinear trends in the evolution of preload loss under both monotonic and cyclic loading, and it represents the combined influence of displacement amplitude, initial preload, and loading type on the reduction of axial clamp force. The model shows that under cyclic loading, loosening develops more rapidly than under monotonic loading; therefore, design criteria should account not only for static resistance but also for the degradation of resistance under cyclic actions, and periodic inspections should be intensified in structures subjected to vibration or dynamic loads. In addition, a higher initial preload reduces the rate of loosening, highlighting the importance of establishing assembly protocols and tightening control during construction and maintenance activities. The increase in preload reduces but does not eliminate loosening, which justifies the need for additional strategies (load control, use of anti-loosening devices).

The study quantifies the effect of transverse displacement and initial preload on the service life of the joint, which is useful to establish trends for design criteria and preventive maintenance planning. However, since the threads were not modeled in order to simplify the analysis, the accuracy in representing the loosening phenomenon is limited. Moreover, the number of case studies should be expanded to enable broader generalization.

The numerical methodology employed can serve as a basis for extending the analysis to more realistic studies and as a reference framework for validating experimental results.

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